CAM6 Ice Formation in Southern Ocean Mixed Phase Clouds

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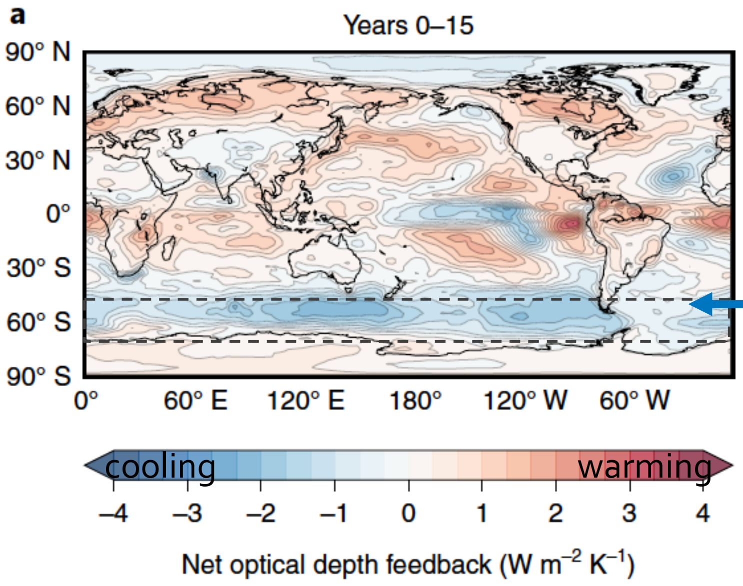
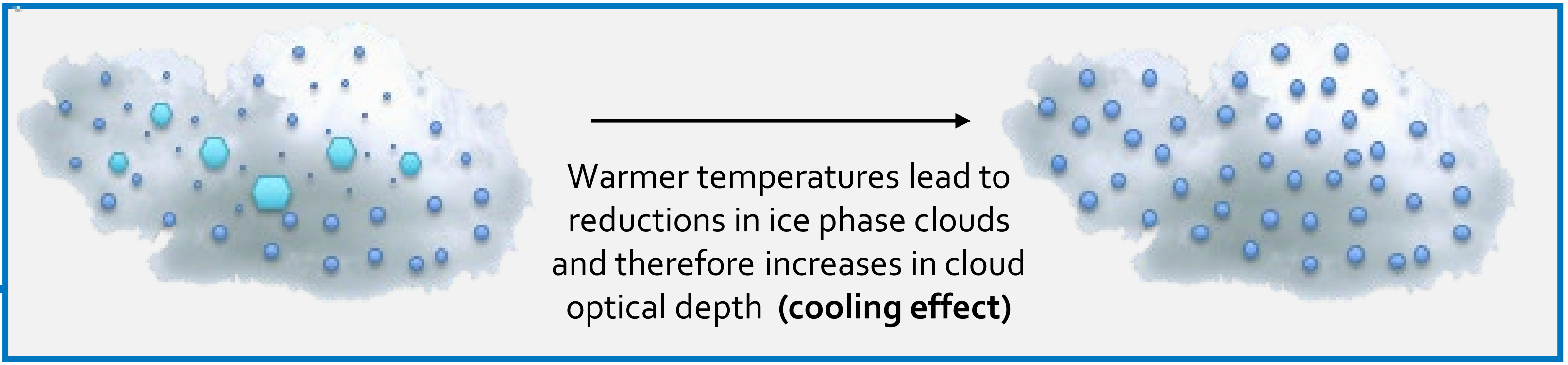
ASR Atmospheric System Research

U.S. DEPARTMENT OF ENERGY | Office of Science

Southern Ocean Clouds are a critical component of the Earth System

Cloud Phase Feedback





ARTICLES
https://doi.org/10.1038/s41561-020-00649-1
nature geoscience
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Equilibrium climate sensitivity above 5 °C plausible due to state-dependent cloud feedback

Jenny Bjordal[1], Trude Storelvmo[1,2]✉, Kari Alterskjær[2,3] and Tim Carlsen[1]

Bjordal et al., 2020

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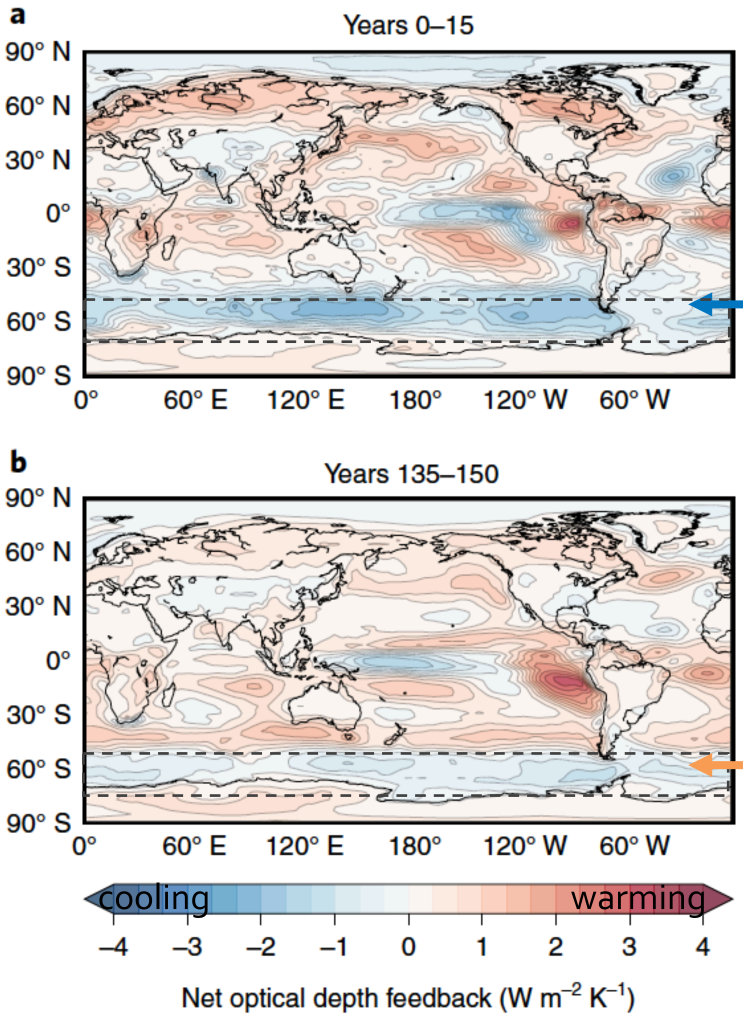
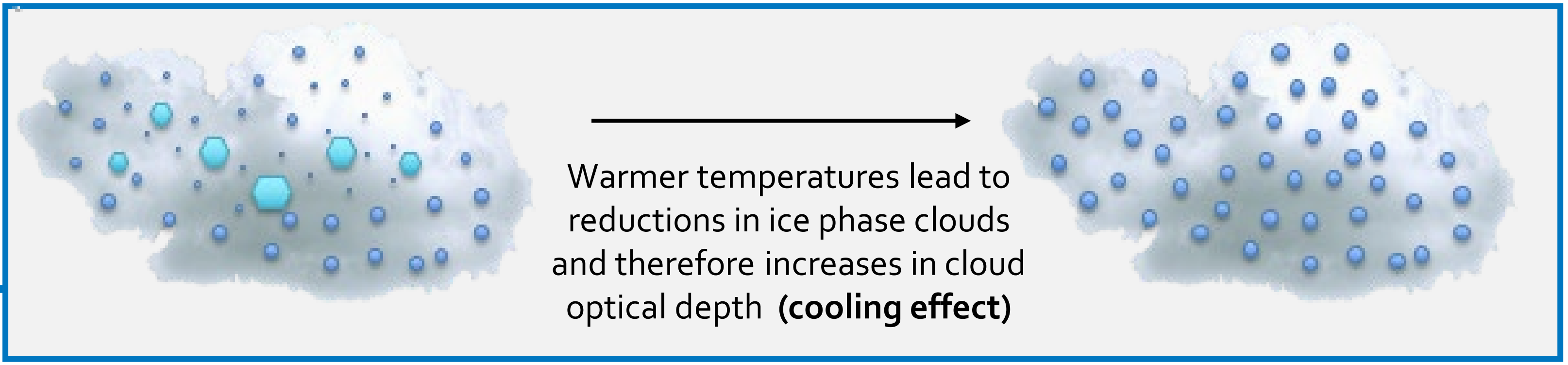
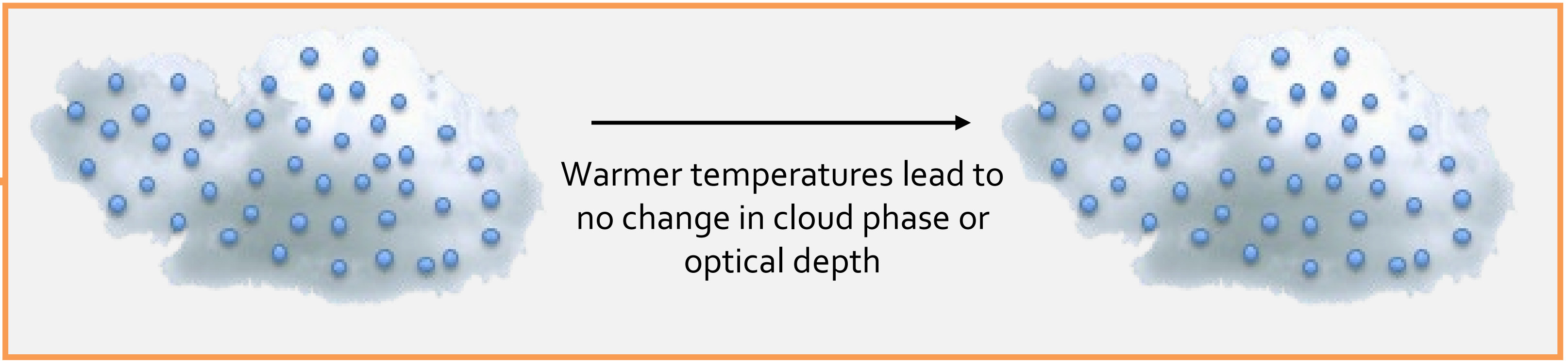




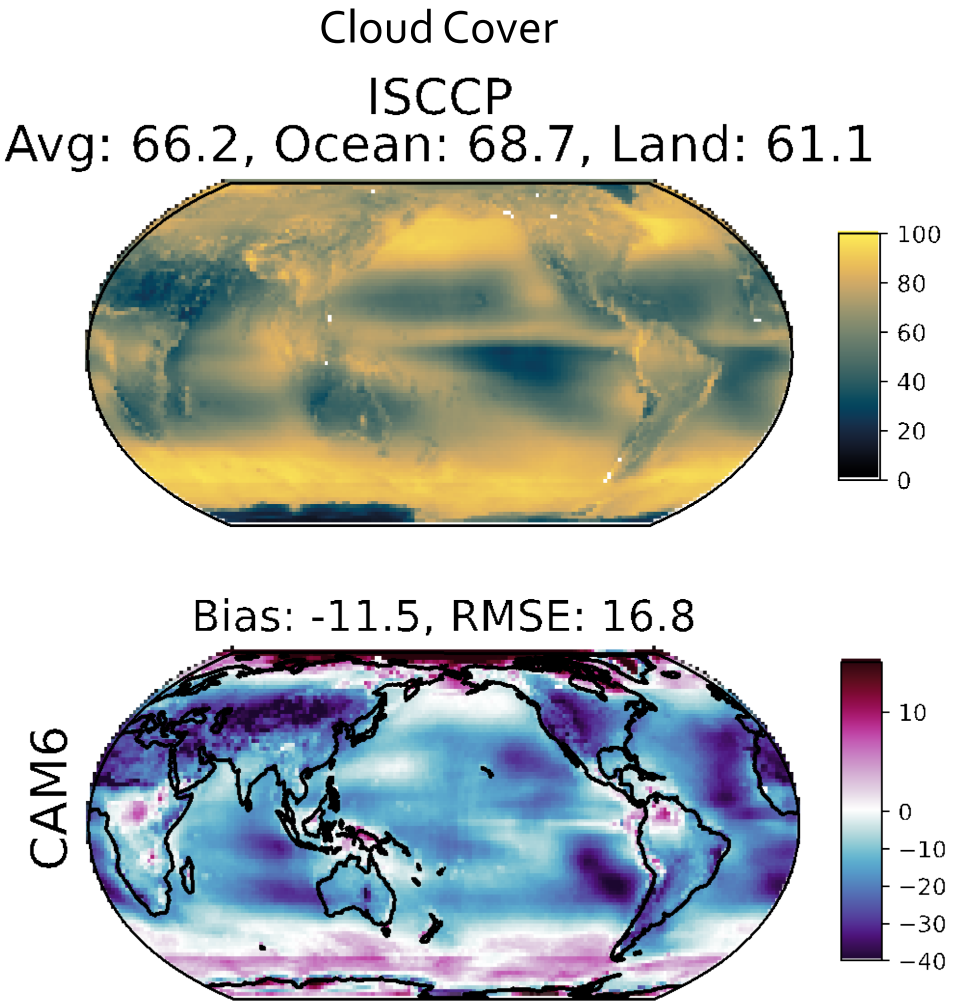
After some amount of warming, all clouds over southern ocean will be liquid, dampening the Southern Ocean negative cloud phase feedback.



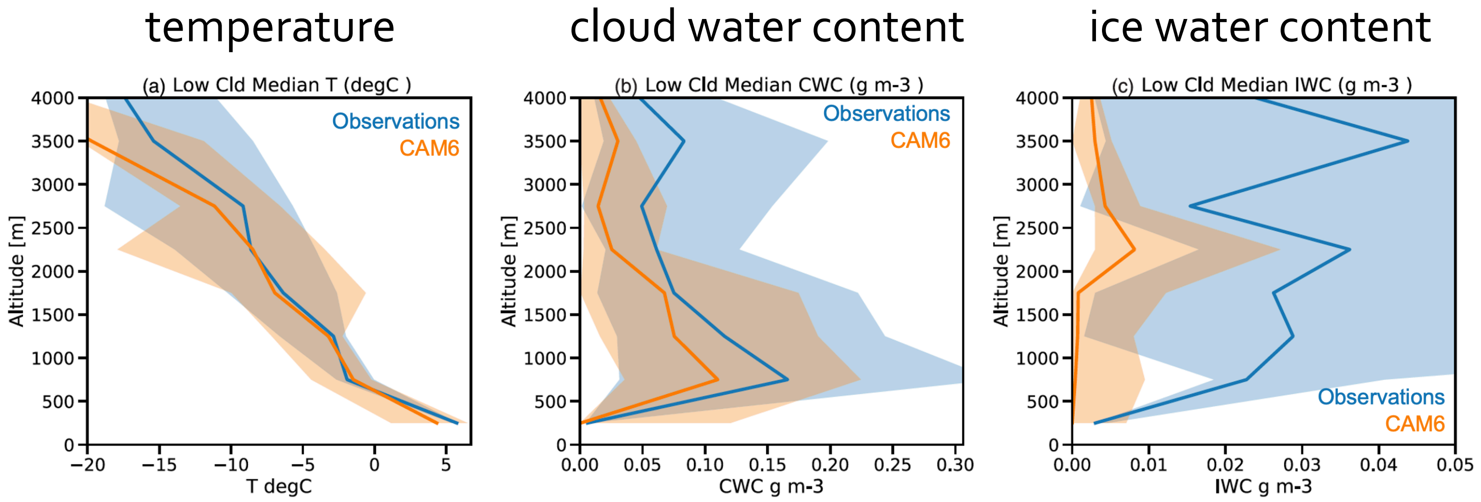
Bjordal et al., 2020

Southern Ocean Clouds continue to challenge Earth System Models

Cloud amount and cloud phase biases remain in the Community Earth System Model



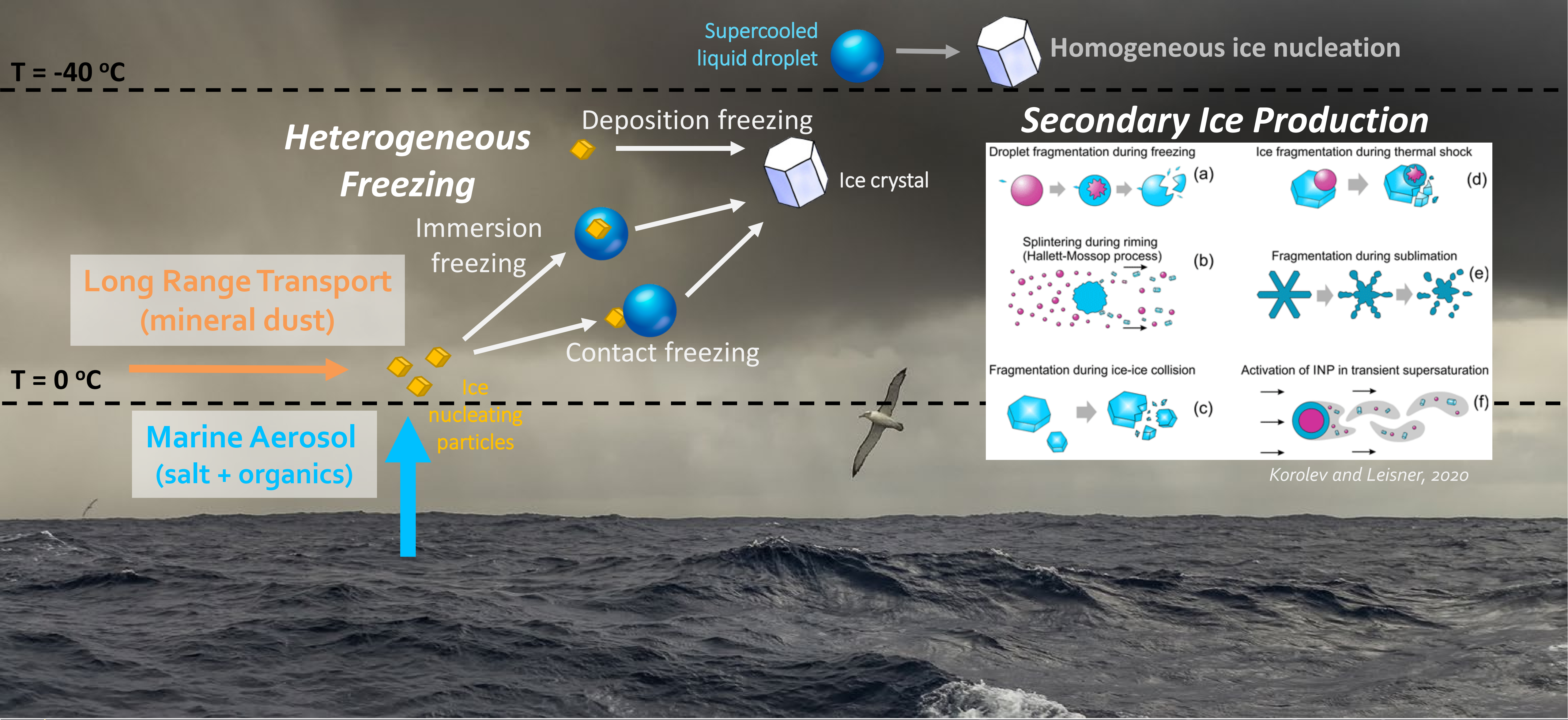
Medeiros et al., 2023



Gettelman et al. (2020)

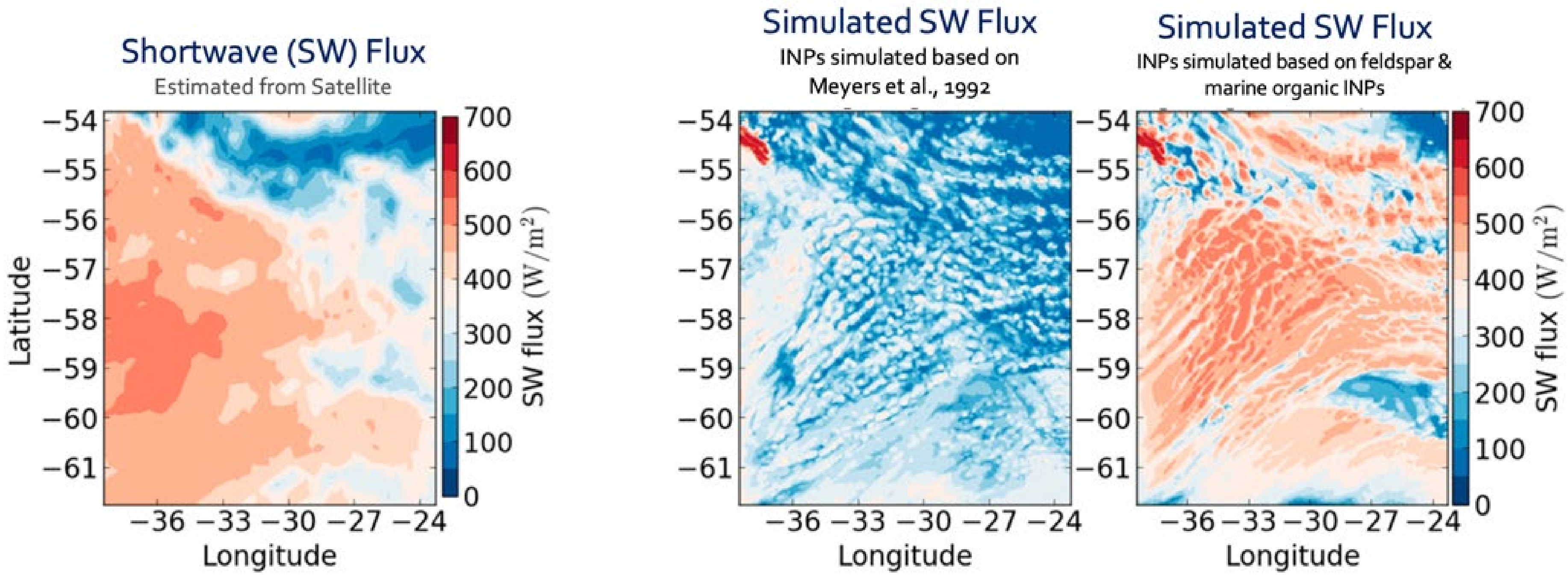
ISCCP = International Satellite Cloud Climatology Project

Southern Ocean aerosol-ice interactions



Hypothesis: *Marine INPs are responsible for the onset of ice formation in Southern Ocean low-level clouds via heterogeneous freezing of cloud droplets*

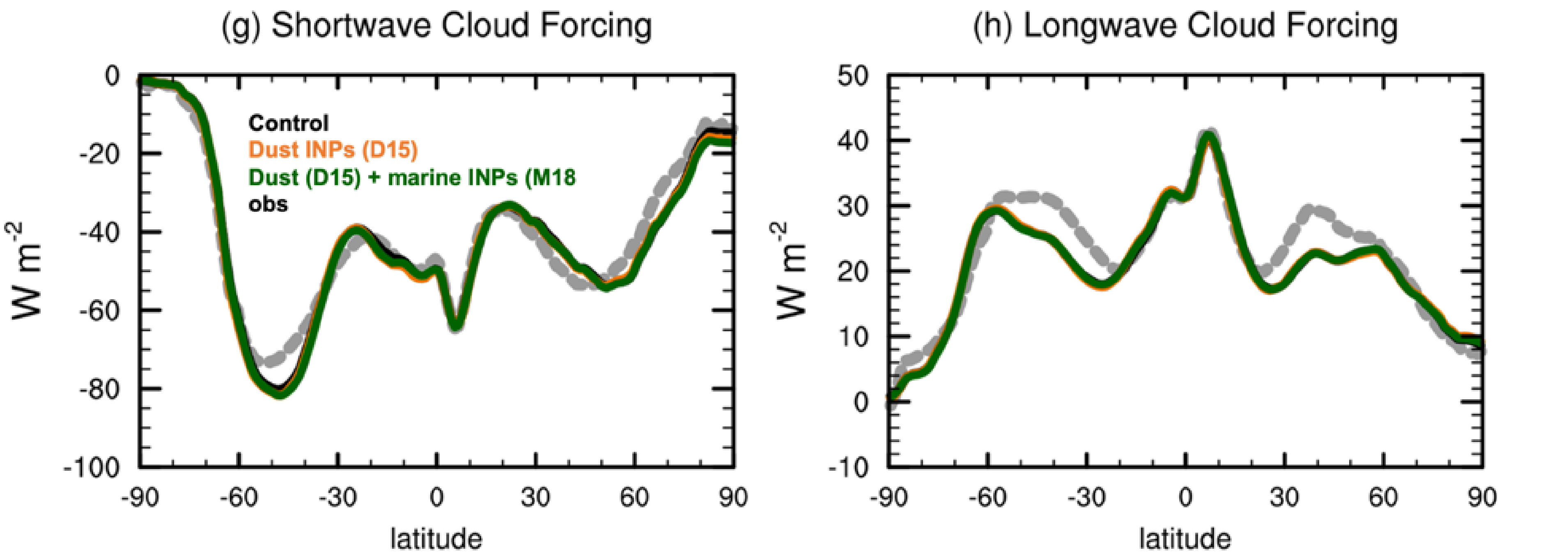
Southern Ocean cloud radiative properties are sensitive to the representation of immersion freezing ice nucleation



Vergara-Temprado et al., 2018

Hypothesis: *Marine INPs are responsible for the onset of ice formation in Southern Ocean low-level clouds via heterogeneous freezing of cloud droplets*

Southern Ocean cloud radiative properties are ***not*** sensitive to the representation of immersion freezing ice nucleation



Zhao et al., 2021

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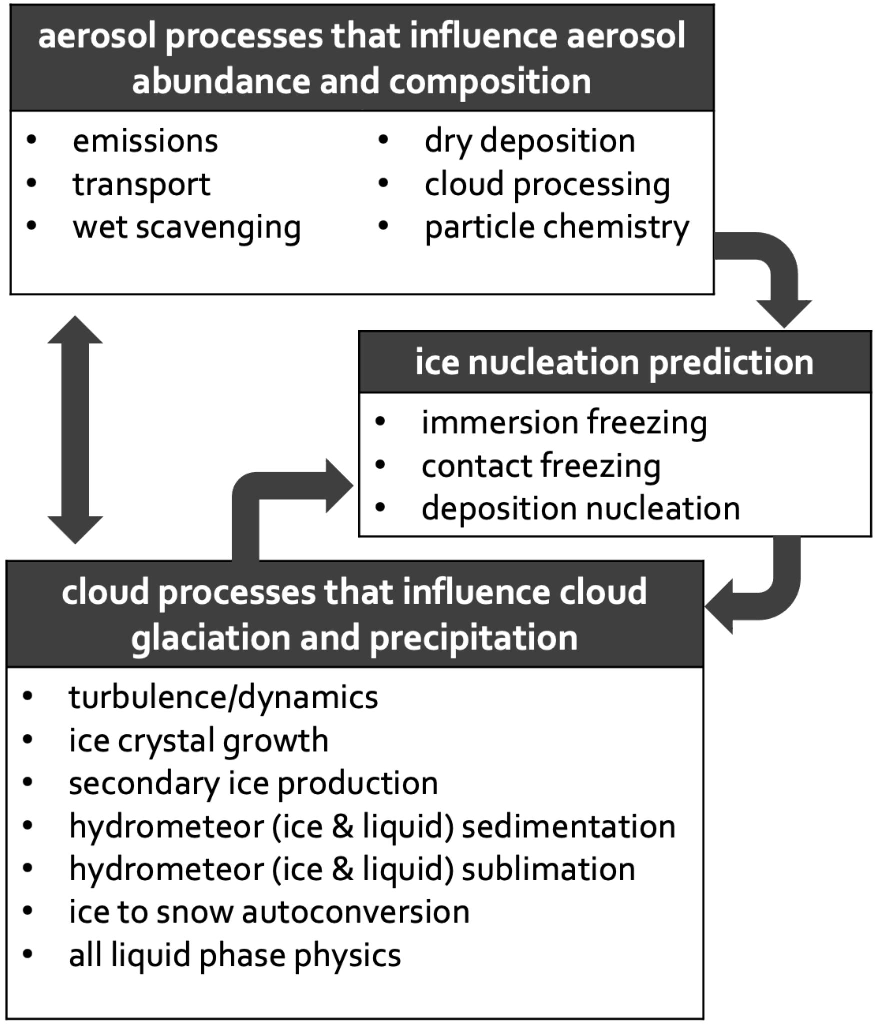


Challenges in using models to determine the role of ice nucleation:

1. Need a comprehensive representation of aerosol and their respective ice nucleation properties.
2. Need to consider the cloud processes that will define the cloud response to ice nucleation.
3. All of these processes are very poorly constrained and difficult to measure.

Burrows et al., 2023

Mixed-Phase Cloud Ice processes in the Community Atmosphere Model version 6 (CAM6)

Model configuration:

- 2˚ latitude x 2˚ longitude
- 32 levels to ~1 hPa
- 30 minute time step
- F2000climo compset
- Development version of cam6 (cam6_3_063), including updates to MG2 (PUMAS)

1. Autoconversion of Cloud Ice to Snow
2. **Heterogeneous Freezing of Cloud Droplets** →
3. Heterogeneous Freezing of Rain to Ice (Bigg 1953; *Barklie and Gokhale*, 1959*)*
4. Ice Multiplication from Rime-Splintering (Cotton, 1986)
5. Accretion of Cloud Ice to Snow

1. Immersion Freezing of Cloud Droplets

   CAM5: Bigg T-dependent (Bigg, 1953)

   CAM6: Stochastic Dust (Hoose et al., 2010)

   NEW: Deterministic Marine and Dust (D15M18)

1. Deposition Freezing of Cloud Droplets

   CAM5: Meyers T-dependent (Meyers, 1992)

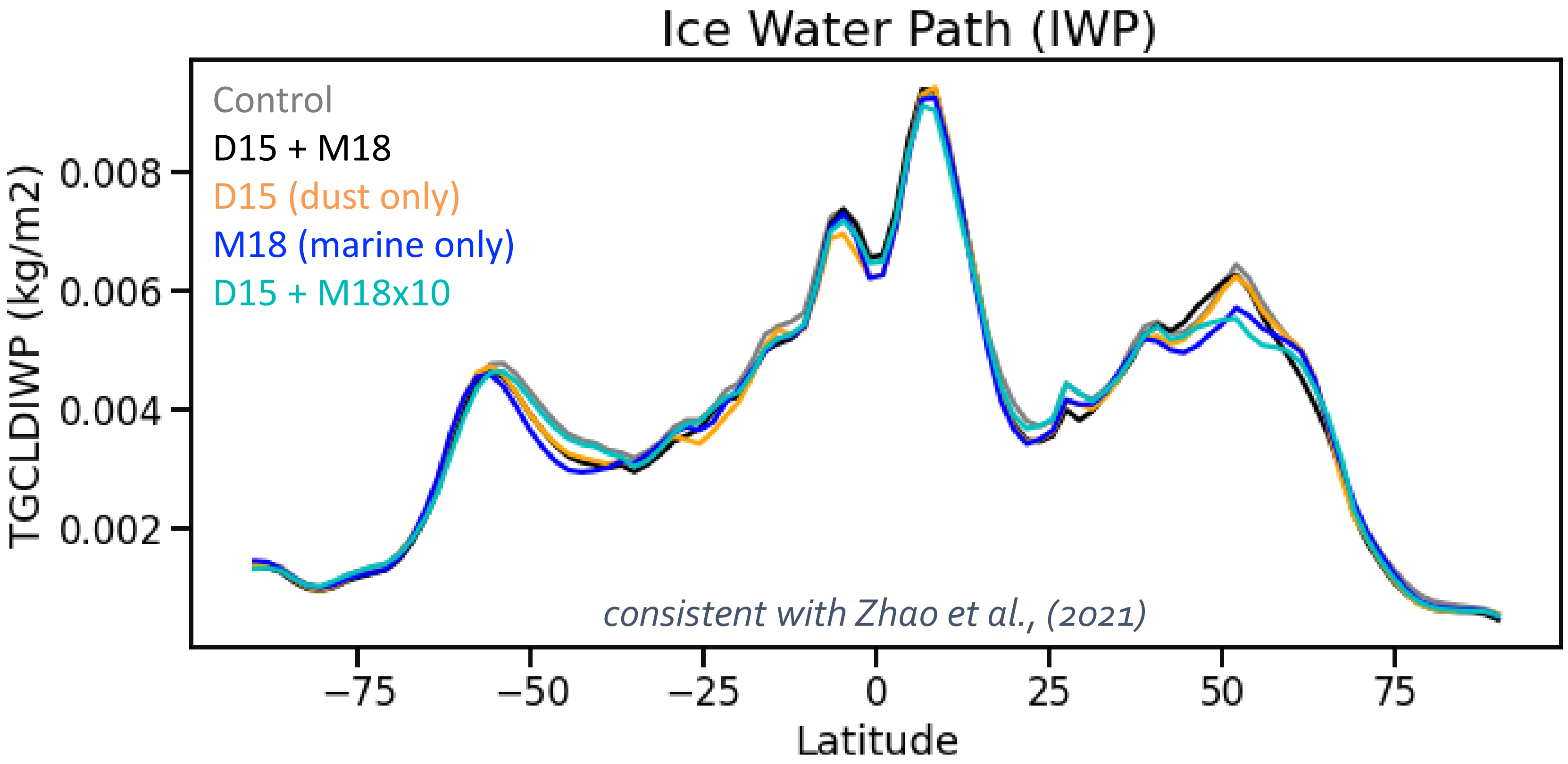
   CAM6: Stochastic Dust (Hoose et al., 2010)

2. Contact Freezing of Cloud Droplets

   CAM5: Young T-dependent (Young, 1974)

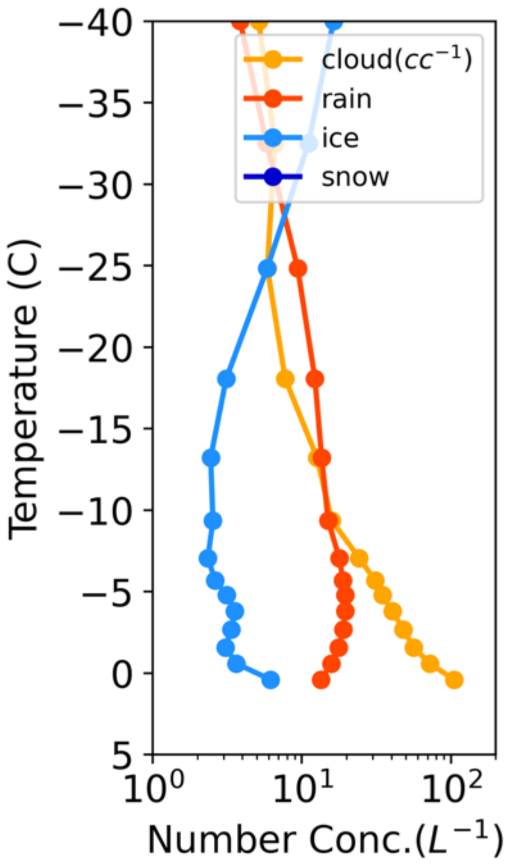
   CAM6: Stochastic Dust (Hoose et al., 2010)

Changes to INPs minimally impact cloud properties in CAM6



No simulated change in ice water path, shortwave or longwave cloud radiative effects due to ice nucleation modifications

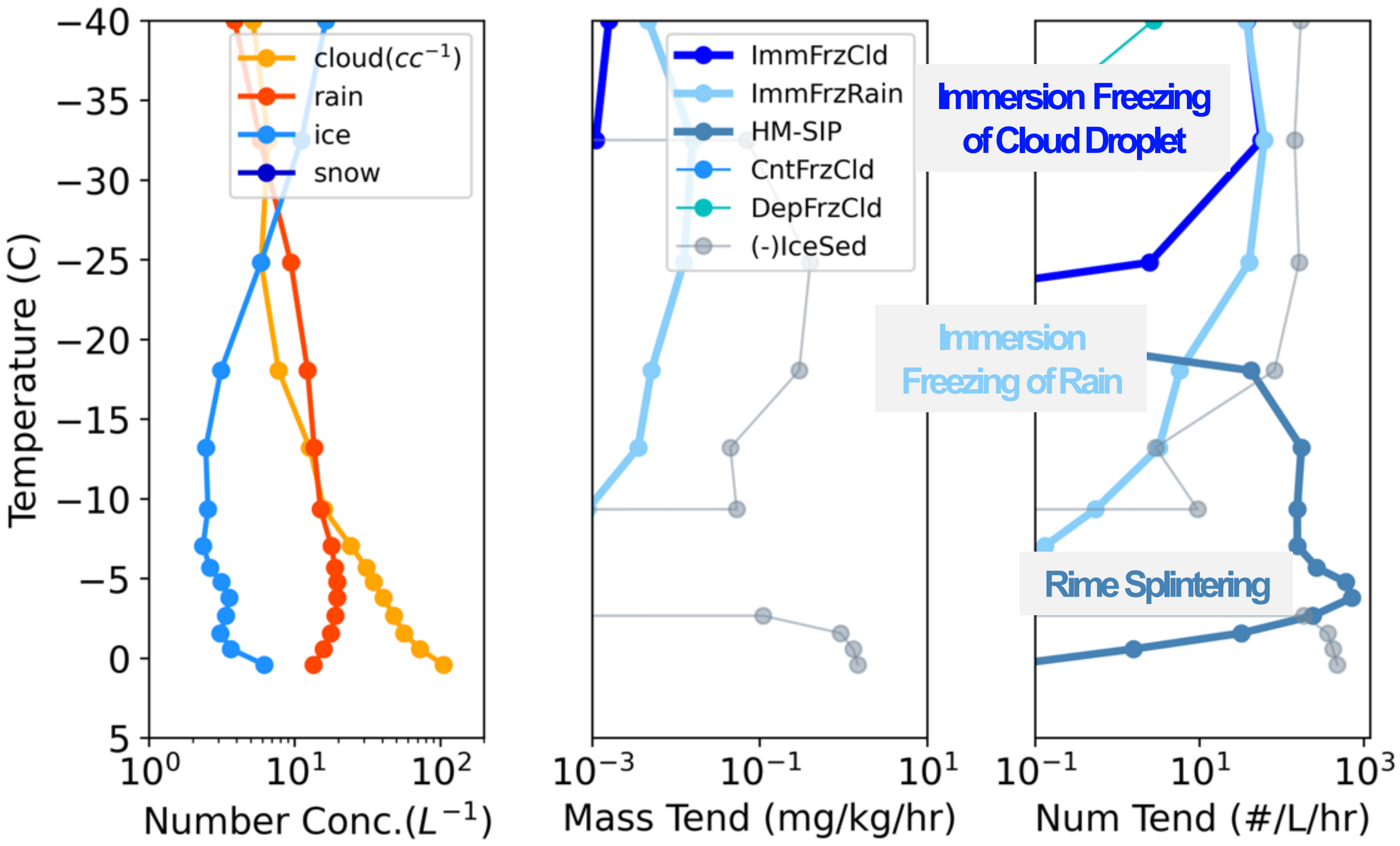
CAM6 microphysics tendencies reveal ice processes that dominate ice formation in Southern Ocean clouds



All clouds, DJF, SO region (-65<Lat<-50 and 80<Lon<165)

CAM6 microphysics tendencies reveal ice processes that dominate ice formation in Southern Ocean clouds

1. **What is immersion freezing of rain?**
2. Why so much rain?



All clouds, DJF, SO region (-65<Lat<-50 and 80<Lon<165)

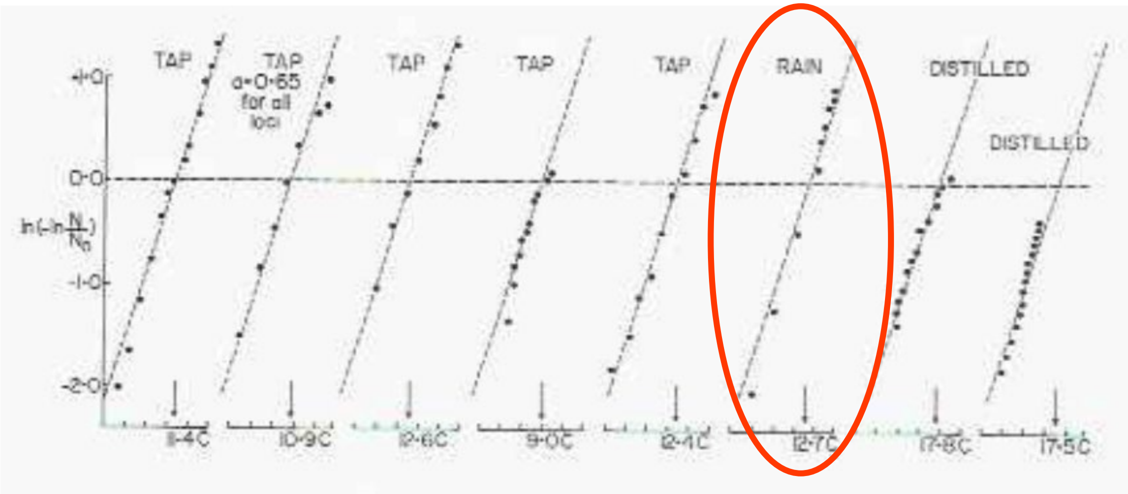
CAM6 immersion freezing of rain

Part III

THE FREEZING OF SUPERCOOLED WATER DROPS

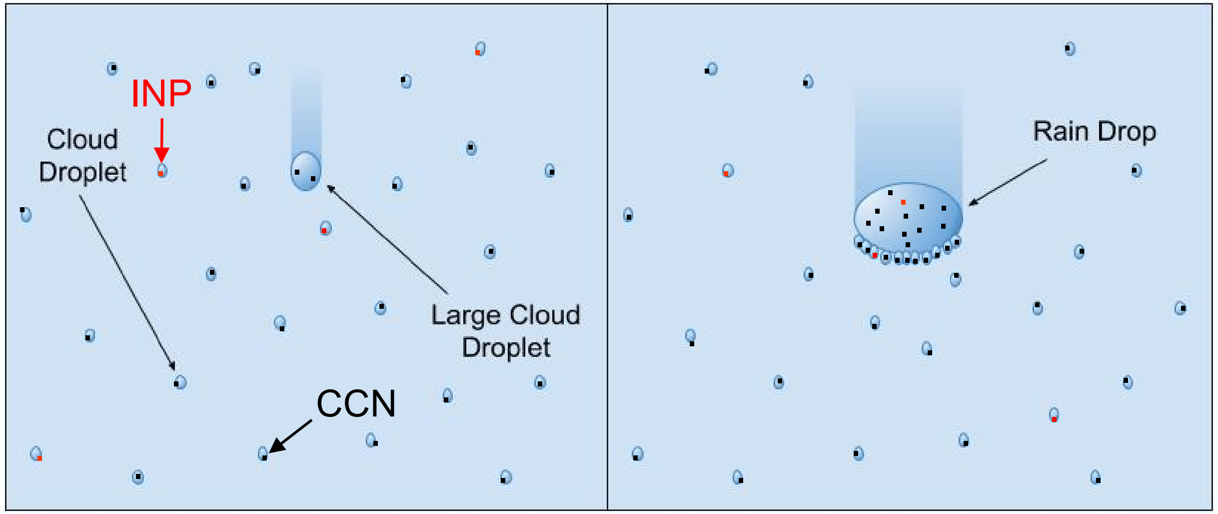
R.H.D. Barklie and N.R. Gokhale

McGill University



Thank you to Paul DeMott and Gabor Vali !

Immersion freezing of rain depends on the cloud's INP population

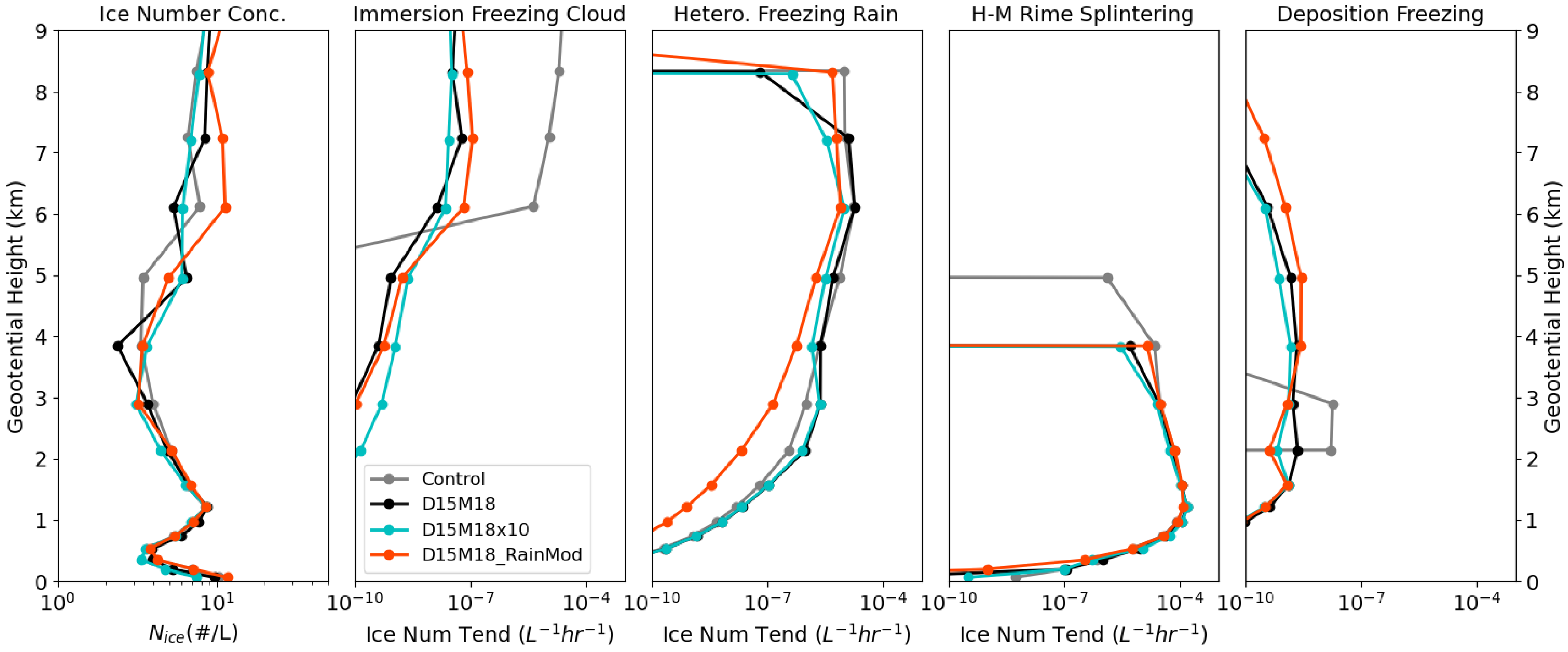


Immersion Freezing dampen factor for the Southern Ocean Region

$$\frac{n_{INP,McGill}}{n_{INPs,\,Southern\ Ocean}} \sim 0.05$$

Modifying heterogeneous freezing of rain

Immersion Freezing dampen factor for the Southern Ocean Region $\frac{n_{INP,McGill}}{n_{INPs,\,Southern\ Ocean}} \sim 0.05$



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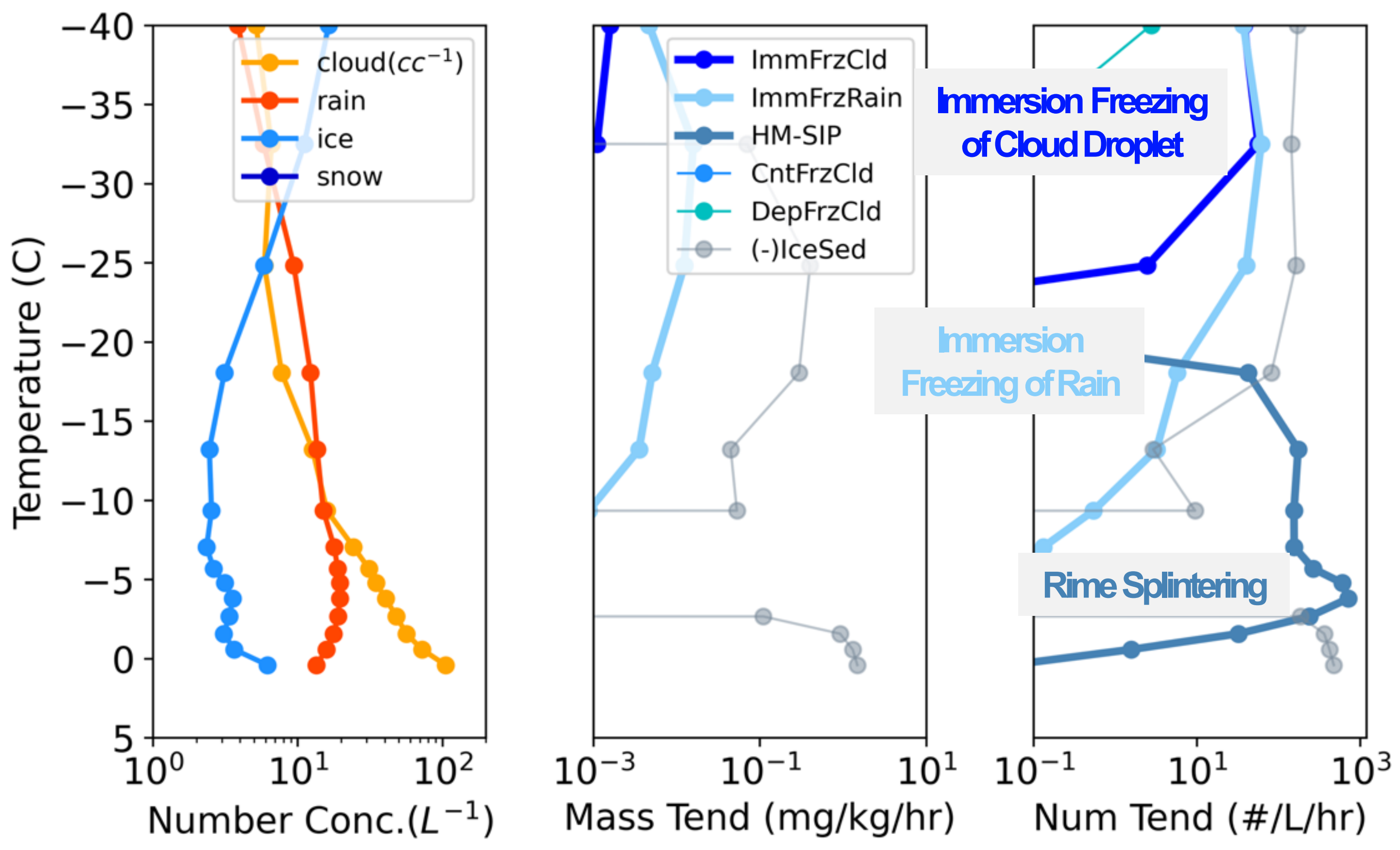

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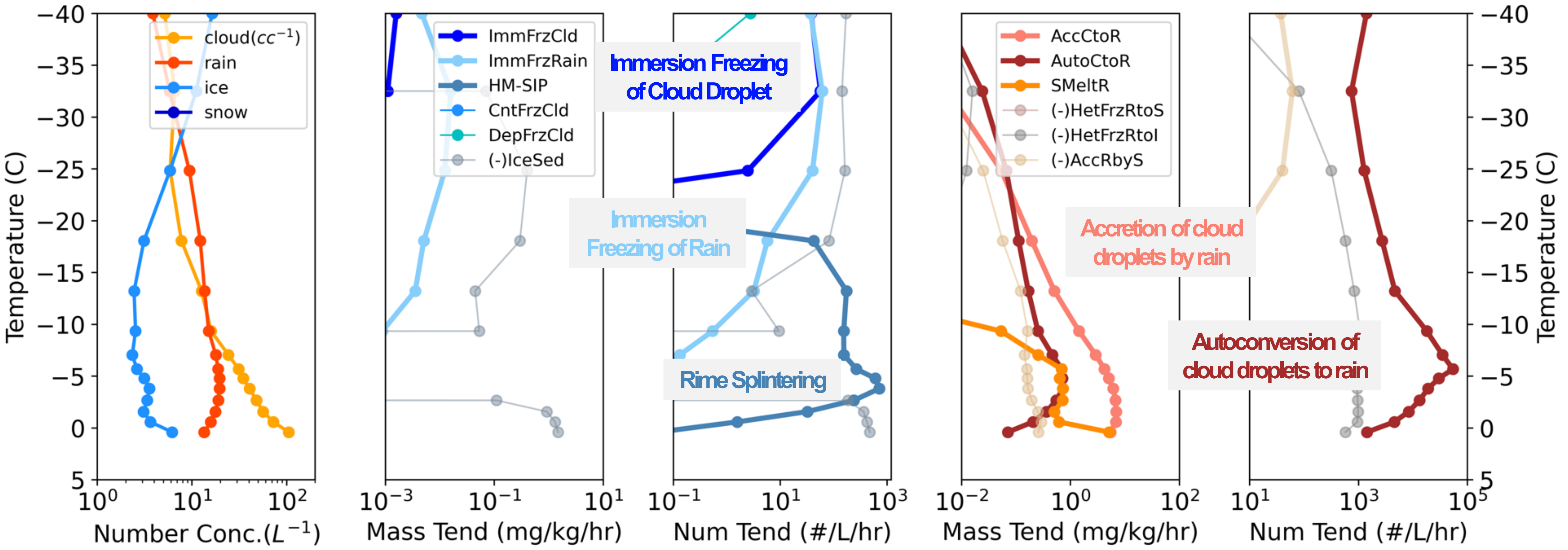

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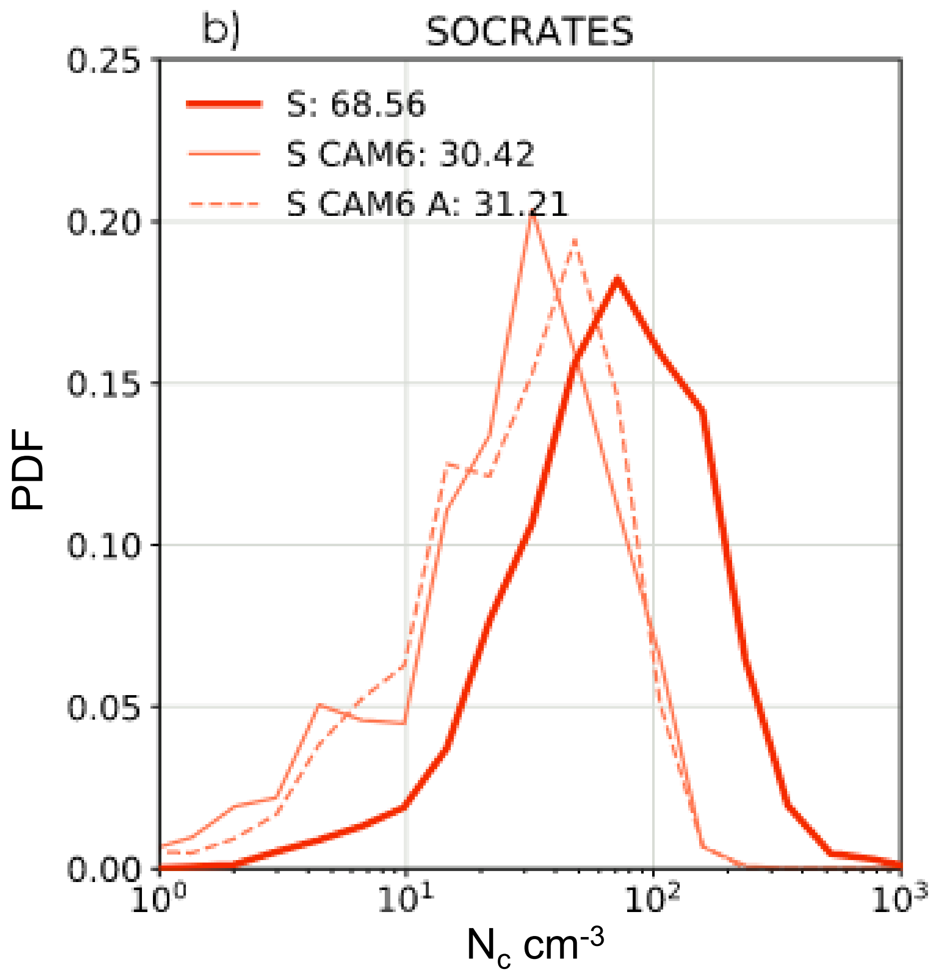
Low cloud droplet number (N_d) bias will drive an overestimated autoconversion rate in CAM6.



I. McCoy et al. (2021)

Autoconversion of cloud droplets to rain

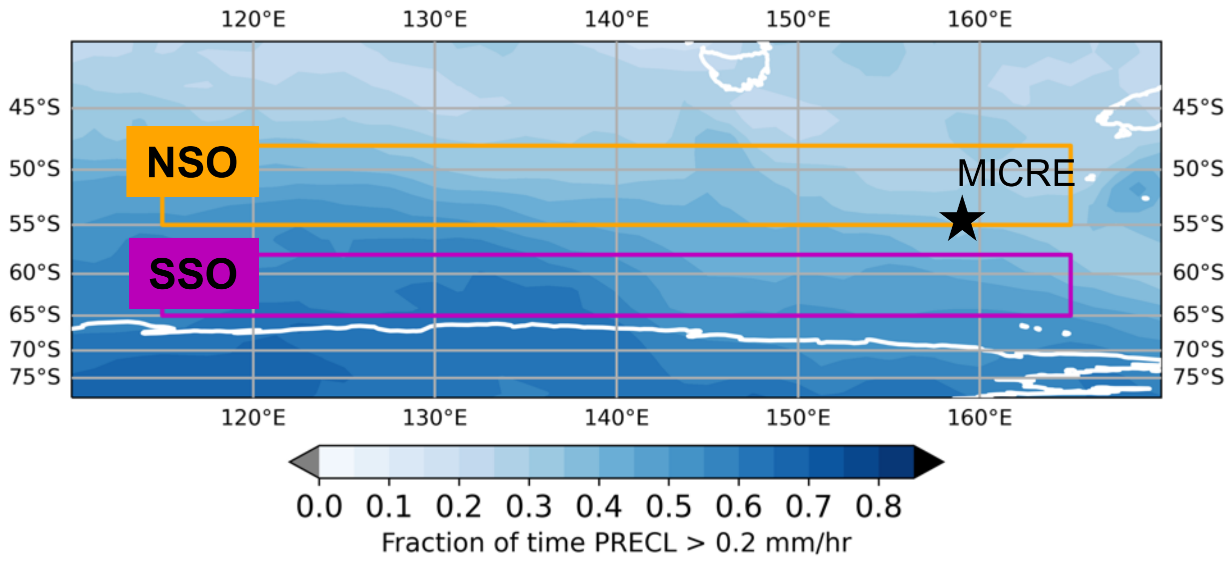
$$\left(\frac{\partial q_r}{\partial t}\right)_{auto} = F_{auto}\, c\, q_c{}^{a}\, N_c{}^{b}$$

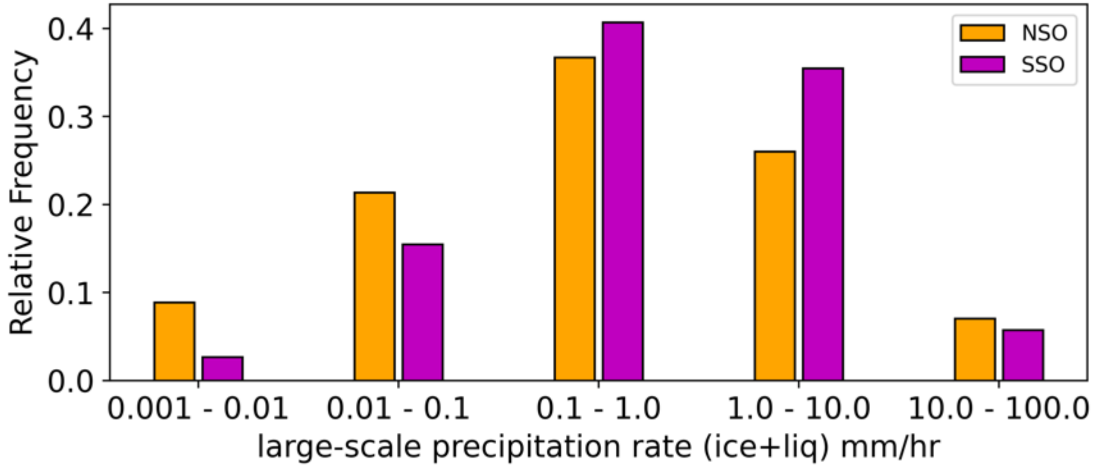
$$\left(\frac{\partial q_r}{\partial t}\right)_{auto} = F_{auto}\, 1350\, q_c{}^{2.47}\, N_c{}^{-1.1}$$

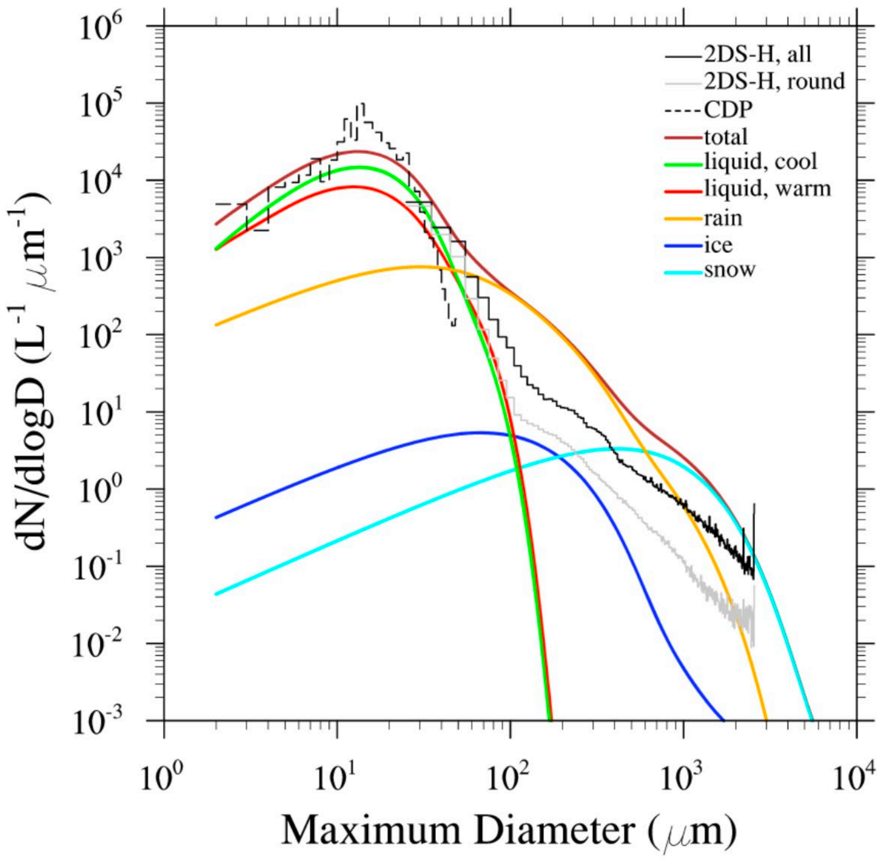
q_c = cloud water content
N_c = cloud droplet number concentration
F_{auto} = autoconversion factor
a = micro_mg_autocon_lwp_exp = 2.47
b = micro_mg_autocon_nd_exp = -1.1
c = coefficient

CAM6 perturbed parameter ensemble (PPE) results:
Autoconversion parameters score in top 3 of parameters that influence SWCF, LWCF, and LWP over the Southern Ocean region.

CAM6 SO clouds are frequently associated with rain rates far exceeding observed mean precipitation at MICRE (0.2 mm/hour; Tansey et al., 2022)







Gettelman et al., 2020

Unique aerosol, cloud, and precipitation conditions continue to drive large uncertainties in CAM6 and other ESMs

Challenging Pristine Conditions:

CAM6 has a low bias in N_d that may be due to low bias in CCN concentrations, poorly resolved sub-grid vertical velocity and supersaturation, and/or overactive consumption of cloud droplets from accretion and autoconversion.

Rain Formation:

A low bias in N_d in SO clouds may result in an over-active autoconversion process.

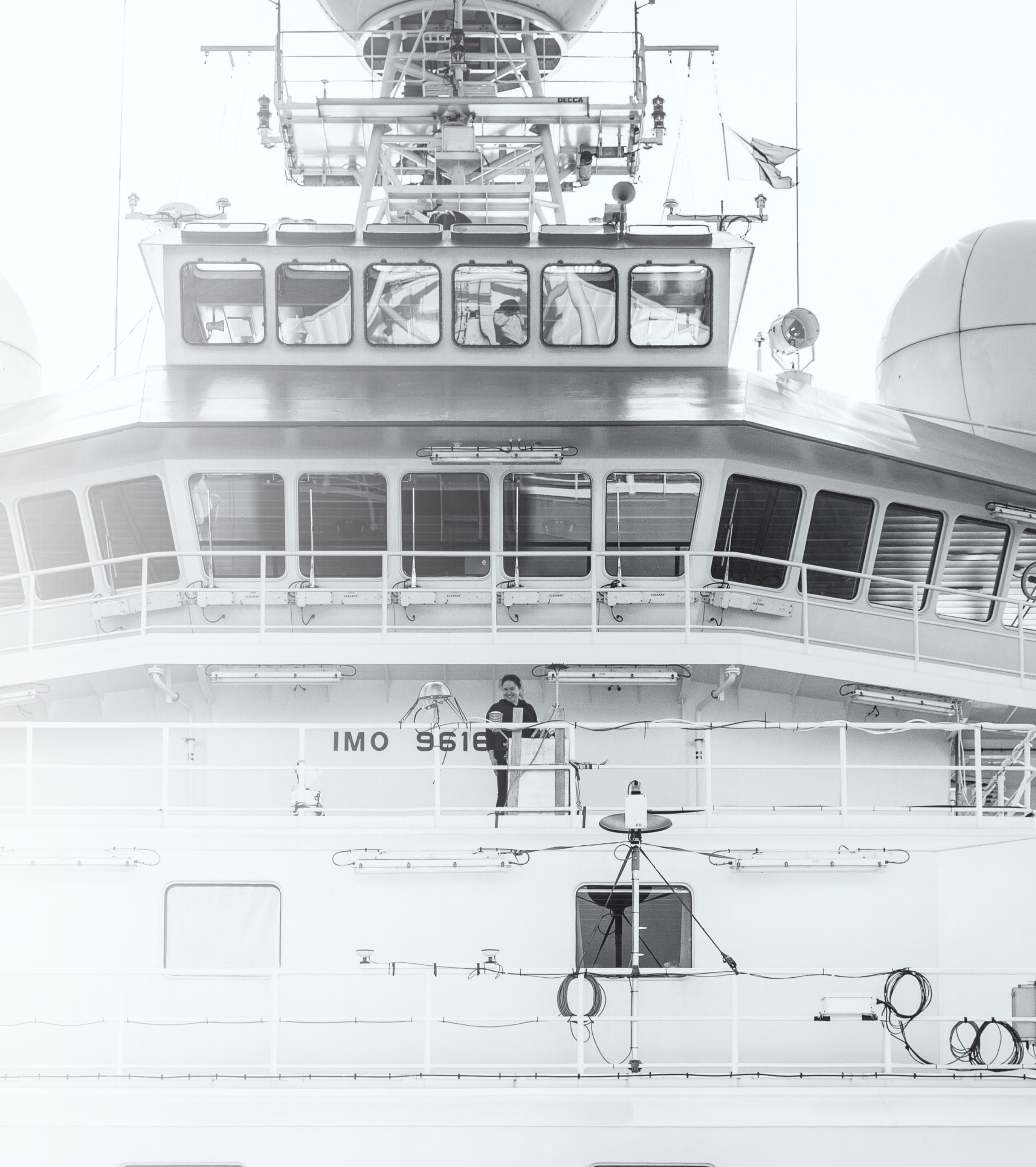
Rain number concentrations in CAM6 far exceed measured INP number concentrations.

Rain Freezing:

Rain heterogeneous freezing dominates initial ice formation and triggers secondary ice production in simulated SO clouds.

Future Work

- Investigate simulated cloud activation processes, including vertical velocity and supersaturation
- Address N_d biases, including consideration of missing aerosol sources/chemistry and scavenging
- Revisit the Bigg 1953 Heterogeneous Freezing of Rain Parameterization – *not the full fix based on preliminary experiments*



Thank you!